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Investigation of the influences of steam injection on the equilibrium combustion products and thermodynamic properties of bio fuels (biodiesels and alcohols)

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HIGHLIGHTS

- Combustion simulation is performed for bio fuels with a reliable model.
- Change of adiabatic flame temperatures and Cp of bio fuels are examined.
- Effects of steam injection on combustion products are investigated.
- Steam injection method diminishes NO emissions considerably.

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ABSTRACT

Even though biodiesel fuels are renewable and have less toxic emission profiles, the most prominent drawback of usage biodiesel in diesel engines is higher NOx compared to petroleum based diesel fuel. However, application of the steam injection technique into diesel engines increases engine performance and reduces NOx emissions. In the present study, the effects of bio fuel combustion with steam injection on the equilibrium combustion products and thermodynamic properties such as specific heat of the exhaust mixtures and adiabatic flame temperatures of bio fuels (biodiesels and alcohols) used commonly, such as canola oil methyl ester (COME), sunflower oil (SFO), cottonseed oil (CSO), soybean oil (SBO), corn oil (CO), rapeseed oil (RSO), ethanol (ETH) and methanol (METH), have been investigated by using a verified simulation code with experimental studies. The simulation code defines the mole fractions of exhaust species at chemical equilibrium depend on equilibrium-constant approach. The combustion products have been comparatively evaluated with respect to increasing steam rate. The results showed that while NO emissions and adiabatic flame temperatures remarkably diminish, specific heats increase with raising steam rate.

1. Introduction and literature survey

The resources of the fossil fuels are depleting and the environmental restrictions with regard to minimizing of pollutant emissions are increasing day by day. It is clear that new solutions must be found to meet the fuel demand and environmental requirements. Bio fuels (biodiesels and alcohols) could be proposed as a solution for the future. They are renewable and may be obtained from various plants. Also, bio fuels are expected as the essential short term alternative fuels in the European Commission's White Paper [1] and so many works on bio fuels have been carried out by engine researchers.

Altin et al. [2] investigated the performance and exhaust emissions of a single cylinder diesel engine fuelled with the vegetable oil fuels and their methyl esters (raw sunflower oil, raw cottonseed oil, raw soybean oil and their methyl esters, refined corn oil, distilled opium poppy oil and refined rapeseed oil). Canakci et al. [3,4] examined the emission and performance parameters of a diesel engine operating with biodiesels and standard diesel fuels by using Artificial Neural Networks (ANNs). The average errors were not greater than 5.5%. Agarwal [5] reviewed the characterization, production and current statuses of vegetable oil, biodiesel and alcohols and he examined the experimental researches and studies considering greenhouse gas emissions, efficiencies, fuel versatility, infrastructure, availability, economics, engine performance and emissions, effect on wear, lubricating oil. Sharma et al. [6] reviewed the latest developments of biodiesel by considering

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Nomenclature

C_v	constant volume specific heat(J g^{-1} K^{-1})
C_p	constant pressure specific heat(J g^{-1} K^{-1})
m	mass (g)
M	molecular weight
NY	total mole number
T	temperature (K)
$K_{\%}$	ratio of the steam mass to the fuel mass

Greek letters

α	atomic number of carbon for diesel fuel
β	atomic number of hydrogen for diesel fuel
γ	atomic number of oxygen for diesel fuel
δ	atomic number of nitrogen for diesel fuel
ε	molar fuel–air ratio
ϕ	equivalence ratio

Subscripts

0	before the combustion
a	air
ad	adiabatic
af	air–fuel mixture
f	fuel
S	stoichiometric
ste	steam

biodegradability, emissions and performance parameters. Patil and Deng [7] carried out a research on producing biodiesel from the non-edible vegetable oils (Jatropha curcas and Pongamia glabra) and edible oils (corn and canola) using potassium hydroxide (KOH) as a catalyst. Fassinou et al. [8] applied the various correlations existing in the literature to some biodiesel samples in order to obtain fuels' higher heating value (HHV) with a high accuracy by comparison to the bomb calorimetric method. Balat [9] reviewed and investigated the production of biodiesel from various non-edible oil seed crops. Gumus et al. [10] examined the influences of injection pressure on the SFC and emissions of a DI diesel engine fuelled with biodiesel–diesel mixtures. Sanli et al. [11] developed a new empirical formula to predict higher heating values of waste frying oils based on regression analysis. They used 35 samples collected from different fast food, fish and hospital restaurants. They obtained more precise results by using this model when compared to other models existing in the literature, the average error was found as 0.37%.

Kannan et al. [12] examined the impact of ethanol addition to jatropha methyl ester (JME) in terms of viscosity reduction and they investigated combustion characteristics such as ignition delay, combustion duration and emissions released from a diesel engine fuelled with blends of ethanol, JME and conventional diesel fuel. Karabektas et al. [13] examined the influences of the mixtures including 15% of ethanol, methanol, biodiesel and vegetable oil (rapeseed oil) with conventional diesel fuel on the emission and performance characteristics of a diesel engine. Carbon monoxide emissions lowered with ethanol, methanol and vegetable oil. Hulwan and Joshi [14] conducted a research on feasibility of using ethanol in diesel–ethanol blends and utilization of ethanol as a co-solvent and improver of biodiesel properties. Saxena et al. [15] examined the utilization of wet ethanol in HCCI engines with exhaust heat recovery to obtain high input energy to ignite wet ethanol and to improve the energy balance of ethanol. Lei et al. [16] examined the effect of a novel emulsifier for ethanol–diesel mixtures on the performance and exhaust emissions of a diesel engine.

Cheng et al. [17] compared the influences of usage of biodiesel with emulsified and fumigated methanol on the performance parameters and emissions characteristics of a direct injection diesel engine. Sayin et al. [18] experimentally examined the influence of injection timing on the performance characteristics and exhaust emissions of a diesel engine operated with diesel–methanol mixtures. Sayin et al. [19] examined the effect of operating parameters, such as injection pressure and timing, on the performance and emission characteristics of a DI diesel engine fuelled with methanol–diesel blends. Zhang et al. [20] examined the influence of fumigation methanol on the combustion characteristics and particulate emissions of a 4-cylinder direct injection diesel engine under various fumigation level and engine loads.

Lin et al. [21] examined the influence of saturated monoglycerides, glycerin, and soap on cold soak filterability of biodiesel produced from canola. Lee et al. [22] experimentally investigated the synthesis of biodiesel from waste canola oil by using supercritical methanol. Also, they examined the influences of reaction conditions on the biodiesel yield. Sayin et al. [23] examined the injection timing on the emission characteristics of a diesel engine operating with canola oil methyl ester–diesel fuel mixtures. Saka and Kusdiana [24] examined the transesterification reaction of rapeseed oil in supercritical methanol without using any catalyst. Wang et al. [25] used a new solid base catalyst in the transesterification of rapeseed oil with methanol to obtain biodiesel.

Candeia et al. [26] examined the effect of soybean biodiesel content on basic properties of biodiesel–diesel mixtures. Bazooyar

Table 1
The properties of the fuels.

	Chemical formula	Density (g/cm^3 at 20 °C)	Lower heat value (MJ/kg)	Cetane number
DF [39]	$C_{14.4}H_{24.9}$	0.84	42.5	45
ETH [42]	C_2H_5OH	0.78	28.4	6
METH [42]	CH_3OH	0.79	20.27	4
COME [23]	$C_{18.08}H_{34.86}O_2$	0.885	38.73	60.4
SFO [2]	$C_{55}H_{105}O_6$	0.878	40.579	45
CSO [2]	$C_{54}H_{101}O_6$	0.874	40.58	45
SBO [2]	$C_{53}H_{101}O_6$	0.872	39.76	37
CO [2]	$C_{56}H_{103}O_6$	0.915	37.825	37.6
RSO [2]	$C_{57}H_{105}O_6$	0.914	37.62	37.6

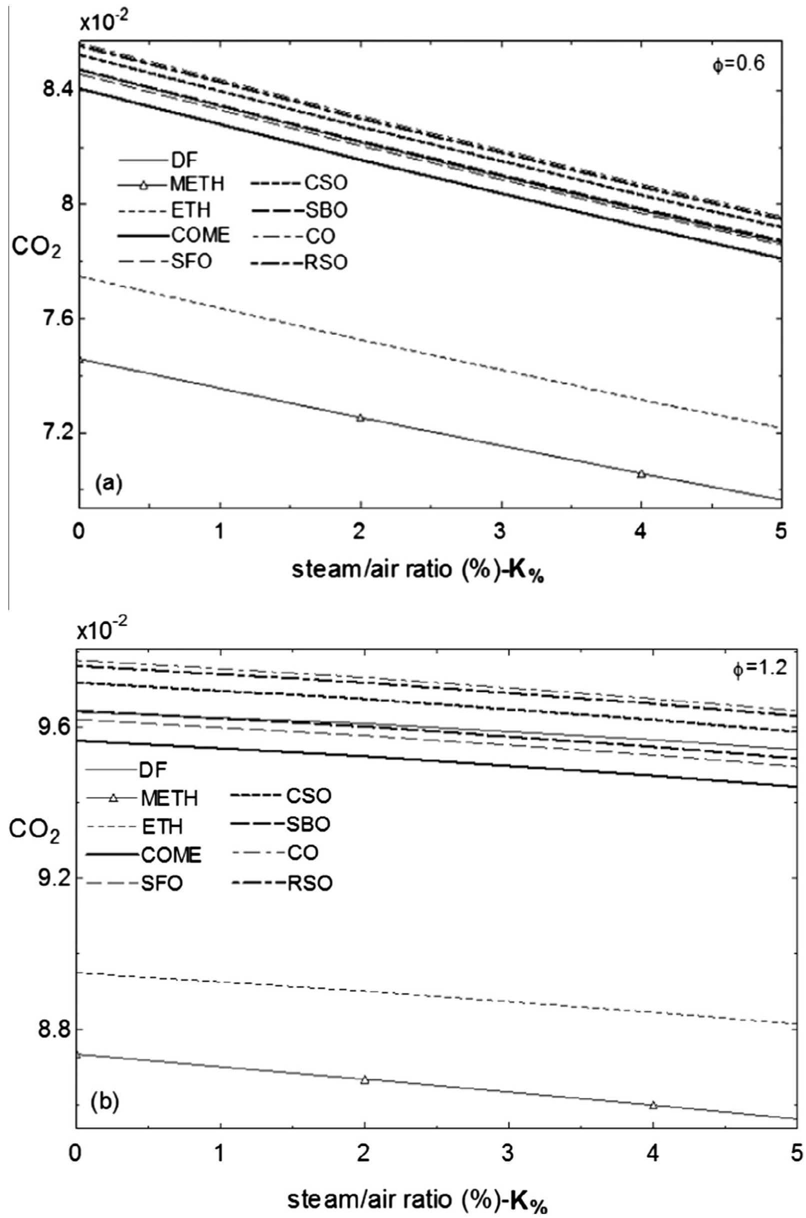


Fig. 1. Equilibrium mole fractions of CO_2 with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

et al. [27] carried out a study to examine combustion characteristics, performance and exhaust emissions of a semi industrial boiler fuelled with petroleum based diesel and biodiesels of rice bran oils, corn, grape seed, sunflower, soybean and olive oils. Randazzo and Sodré [28] examined the influences of diesel oil–soybean biodiesel mixtures on the exhaust emissions released from a passenger vehicle. Moreover, they studied the effects of ethanol addition to diesel oil–soybean biodiesel blends. The results indicated that carbon dioxide (CO_2) and oxides of nitrogen (NOx) emissions raise, whilst carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) emissions minimize, the addition of ethanol to fuel blend decreases NOx and CO_2 concentration while CO, HC and PM emissions rise. Santos et al. [29] conducted an investigation on the performance, the main characteristics and advantages of low linolenic acid soybean (LL). Ozener et al. [30] investigated the influences of biodiesel produced from soybean oil and its blends with the petroleum based diesel fuel on the performance, combustion and emission characteristics of a single-cylinder direct injection diesel engine. In the results, it was demonstrated that the torque lowered with increasing brake-specific fuel consumption (BSFC). CO and HC emissions decreased and NOx and CO_2 emissions increased due to addition of the biodiesel to conventional diesel fuel. Also, the ignition delay and peak heat release rate in the premixed combustion decreased with biodiesel addition.

Based on the literature survey it can be said that the utilization of biodiesel fuels in diesel engines leads to decreasing of CO [12,17,28,30], PM [17,28], HC [12,17,28,30] and smoke opacity [12]. However, NOx emissions remarkably increase [12,17,28,30]. There are various methods so as to reduce NOx emissions such as exhaust gas recirculation (EGR), the water usage methods (direct water injection (DWI), fumigation, emulsion). Since EGR decrease the engine performance considerably [31,32], classical water usage methods lower the quality of lubrication oil and increase the attrition rate of moving parts of the engine [33],

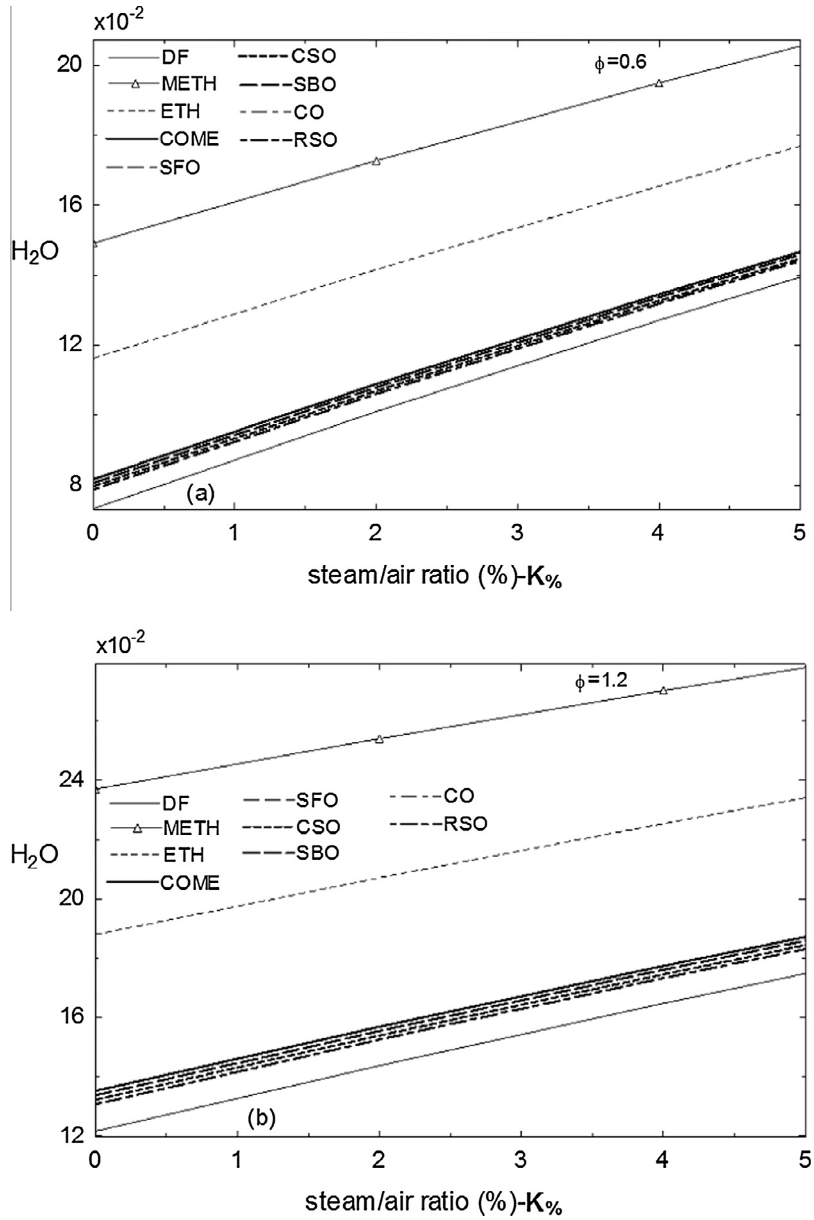


Fig. 2. Equilibrium mole fractions of H_2O with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

recently, steam injection method has been proposed and used by engine researchers [33–39,43–45] in order to reduce NOx emissions and improve the engine performance.

This study reports the influences of steam injection on the combustion of bio fuels (biodiesels and alcohols) commonly used such as COME, SFO, CSO, SBO, CO, RSO, ETH and METH in terms of the thermodynamic properties and equilibrium combustion products including NO. In this study, a verified simulation code with experimental studies [37–39,43–46] and computer programs [40] have been used to determine and compare the combustion characteristics of bio fuels and conventional diesel fuel. In the literature, there is no such a comprehensive study examining the influences of steam injection on the characteristics of bio fuel combustion. Thus, this work has a remarkable novelty to make up for the deficiency in the literature.

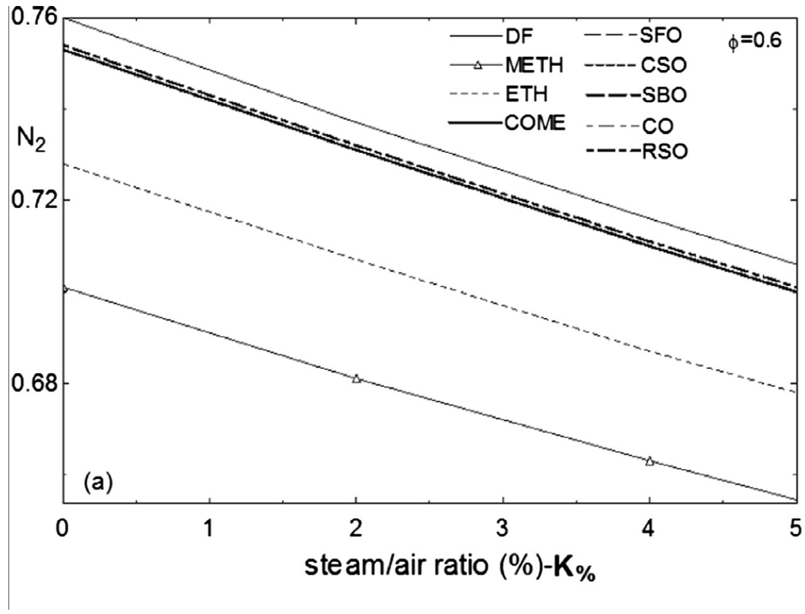
2. Theoretical model of the equilibrium combustion products and thermodynamic properties

Theoretical combustion simulation of bio fuels with steam injection is performed by using a verified code with experiments [37–39,43–46] and two softwares (CHEMKIN and GASEQ) [40] so as to predict adiabatic flame temperatures, specific heats and combustion products (CO_2, H_2O, N_2, O_2, CO, H_2, H, O, OH, NO). The combustion reaction used in the present model is written below:

For low temperature and lean combustion conditions;

$$\begin{aligned} &T \leqslant 1000\ \mathrm{K} \quad 1 < \phi \\ &\varepsilon\phi(C_\alpha H_\beta O_\gamma N_\delta) + [(0.21 \cdot O_2) + (0.79 \cdot N_2)] + y \cdot H_2O \rightarrow \\ &\upsilon_1 CO_2 + \upsilon_2 H_2O + \upsilon_3 N_2 + \upsilon_4 O_2 + \upsilon_5 CO + \upsilon_6 H_2 \end{aligned} \tag{1}$$

where from chemical equation balancing for atoms:



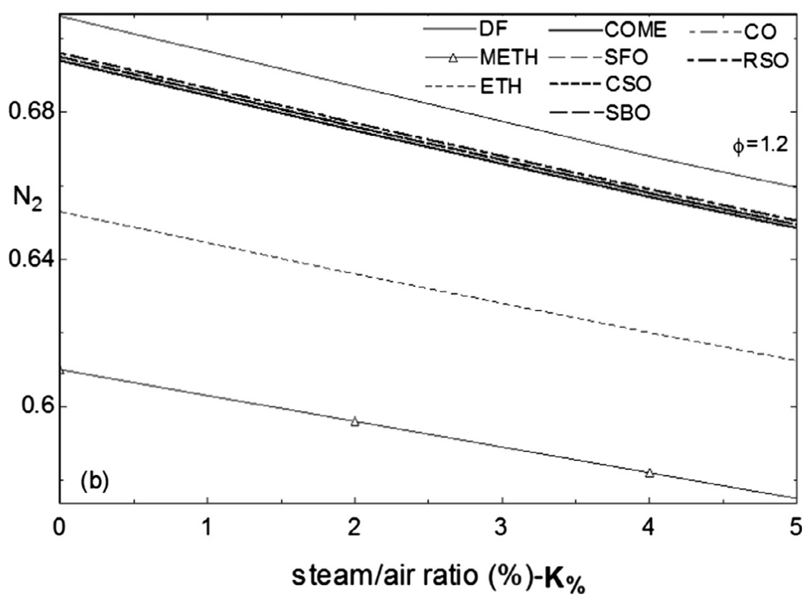


Fig. 3. Equilibrium mole fractions of N_2 with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

$$\upsilon_1 = \varepsilon\phi\alpha; \quad \upsilon_2 = \frac{\varepsilon\phi\beta}{2} + y; \quad \upsilon_3 = \frac{\phi\varepsilon\delta}{2} + 0.79;$$
$$\upsilon_4 = \phi(-0.21) + 0.21; \quad \upsilon_5 = \upsilon_6 = 0 \tag{2}$$

where α, β, γ, δ are atomic numbers of carbon, hydrogen, oxygen, nitrogen of fuel. ϕ is the equivalence ratio, ε is molar fuel–air ratio, y is the molar injection ratio of the steam which are obtained as follows:

$$\phi = \frac{m_f/m_a}{(m_f/m_a)_S} \tag{3}$$

$$\varepsilon = \frac{0.21}{(\alpha - \frac{\gamma}{2} + \frac{\beta}{4})} \tag{4}$$

$$(m_f/m_{air})_S = \frac{\varepsilon \cdot (12.01\alpha + 1.008\beta + 16\gamma + 14.01\delta)}{28.85} \tag{5}$$

$$y = \frac{K_{\%} M_{air}}{M_{ste}} \tag{6}$$

where M_{ste} and M_{air} are the total molecular weights of the steam and air, K is the ratio of the steam mass to the air mass and it is given as follows:

$$K_{\%} = \frac{m_{ste}}{m_{air}} \tag{7}$$

where m_f, m_{ste} and m_{air} are the masses of the fuel, steam and air.

For low temperature and rich combustion conditions;

$$T \leqslant 1000\,\mathrm{K} \quad 1 \geqslant \phi$$
$$\varepsilon\phi(C_\alpha H_\beta O_\gamma N_\delta) + [(0.21 \cdot O_2) + (0.79 \cdot N_2)] + y \cdot H_2O \rightarrow \tag{8}$$
$$\upsilon_1 CO_2 + \upsilon_2 H_2O + \upsilon_3 N_2 + \upsilon_4 O_2 + \upsilon_5 CO + \upsilon_6 H_2$$

where, from chemical equation balancing for atoms:

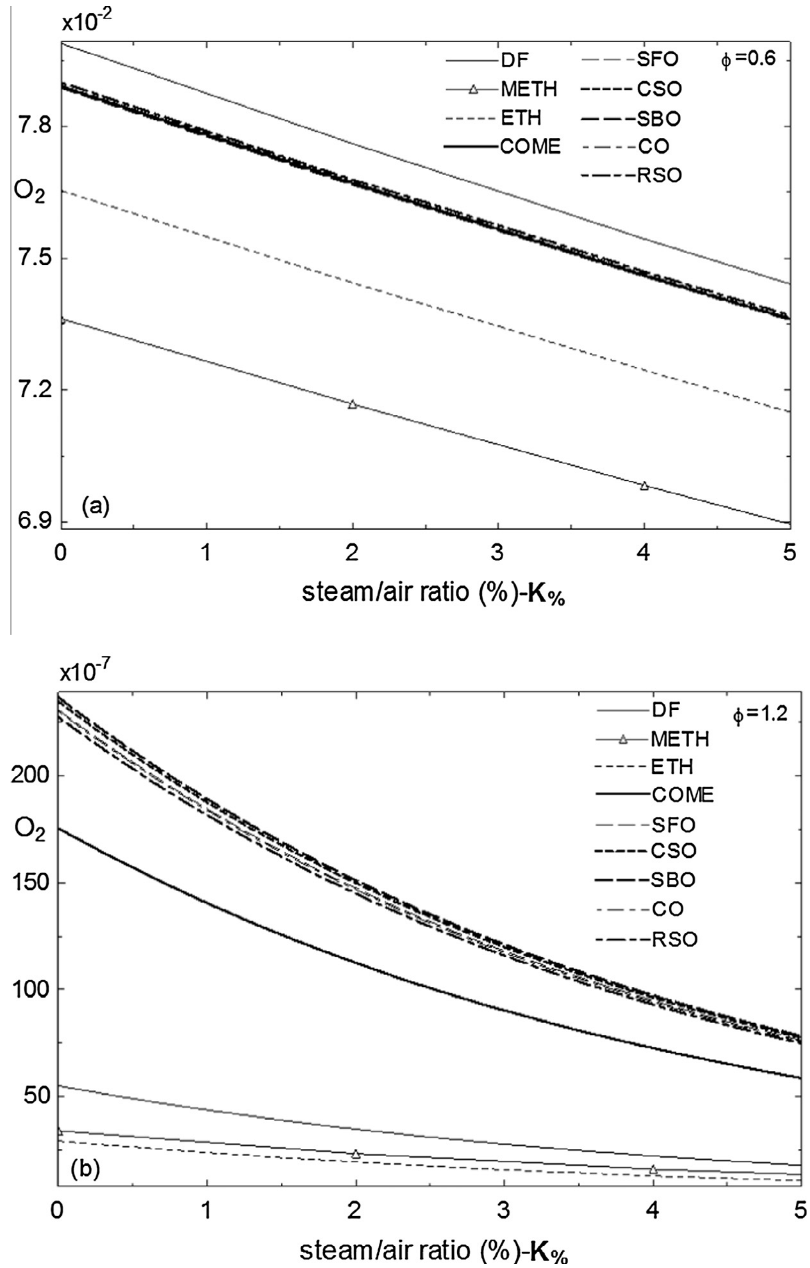


Fig. 4. Equilibrium mole fractions of O_2 with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

$$\upsilon_1 = \varepsilon\phi\alpha - \upsilon_5; \quad \upsilon_2 = \varepsilon\phi(\gamma - 2\alpha) + 0.42 + y + \upsilon_5;$$
$$\upsilon_3 = \frac{\phi\varepsilon\delta}{2} + 0.79; \quad \upsilon_4 = 0; \quad \upsilon_6 = 0.42(\phi - 1) - \upsilon_5;$$
$$\upsilon_5 = \frac{K\upsilon_6\upsilon_1}{\upsilon_2} \tag{9}$$

where K is obtained as below [41]:

$$\ln K = 2.743 - 1.761/t - 1.611/t^2 + 0.2803/t^3 \tag{10}$$

where $t = T/1000$ and in Kelvin.

For high combustion condition;

$$T > 1000\,\mathrm{K}$$
$$\varepsilon\phi(C_\alpha H_\beta O_\gamma N_\delta) + [(0.21 \cdot O_2) + (0.79 \cdot N_2)] + y \cdot H_2O \rightarrow$$
$$\upsilon_1 CO_2 + \upsilon_2 H_2O + \upsilon_3 N_2 + \upsilon_4 O_2 + \upsilon_5 CO + \upsilon_6 H_2 + \upsilon_7 H + \upsilon_8 O + \upsilon_9 OH + \upsilon_{10} NO \tag{11}$$

where from chemical equation balancing for atoms:

$$\begin{aligned}
&\varepsilon\phi\alpha = (y_1 + y_5)\mathrm{NY}\\
&\varepsilon\phi\beta + 2y = (2y_2 + 2y_6 + y_7 + y_9)\mathrm{NY}\\
&\varepsilon\phi\gamma + 2 \cdot 0.21 + y = (2y_1 + y_2 + 2y_4 + y_5 + y_8 + y_9 + y_{10})\mathrm{NY}\\
&\varepsilon\phi\delta + 2 \cdot 0.79 = (2y_3 + y_{10})\mathrm{NY}
\end{aligned} \tag{12}$$

where NY is the total mole number and may be described as follows:

$$\mathrm{NY} = \sum_{i=1}^{10} \upsilon_i \quad \text{and} \quad \sum_{i=1}^{10} y_i - 1 = 0 \tag{13}$$

The mole fractions of the combustion species are written with respect to y_3, y_4, y_5, y_6.

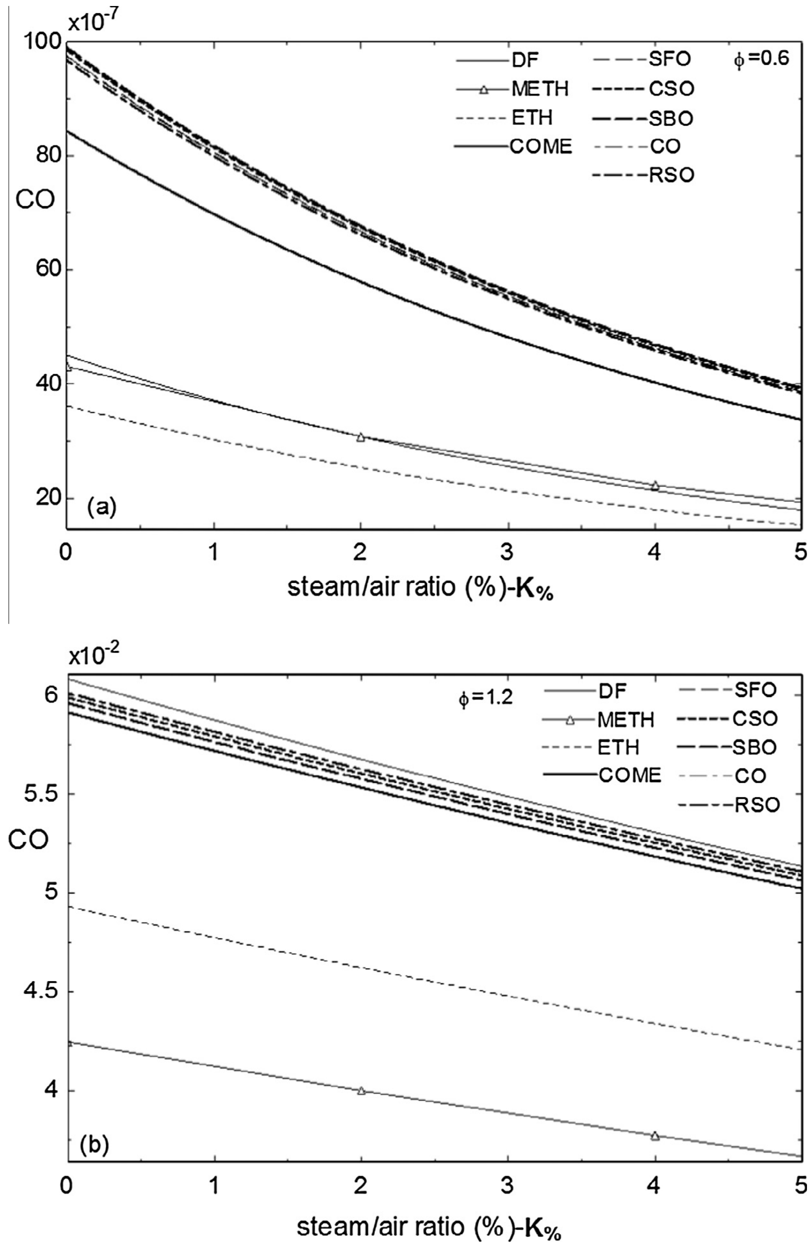


Fig. 5. Equilibrium mole fractions of CO with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

$$
\begin{aligned}
&y_7 = c_1 y_7^{1/2}, \quad y_8 = c_2 y_4^{1/2}, \quad y_9 = c_3 y_4^{1/2} y_6^{1/2}, \\
&y_{10} = c_4 y_4^{1/2} y_3^{1/2}, \quad y_2 = c_5 y_4^{1/2} y_6, \quad y_1 = c_6 y_4^{1/2} y_5 \\
&c_1 = \frac{K_1}{P^{1/2}}, \quad c_2 = \frac{K_2}{P^{1/2}}, \quad c_3 = K_3 \\
&c_4 = K_4, \quad c_5 = K_5 P^{1/2}, \quad c_6 = K_6 P^{1/2}
\end{aligned} \tag{14}
$$

where K_i is the equilibrium constant and calculated by using Eq. (15).

$$
\log K_i = A \ln\left(\frac{T}{1000}\right) + \left(\frac{B}{T}\right) + C + (D\ T) + (E\ T^2) \tag{15}
$$

The A, B, C, D and E constants are taken from JANAF tables and these equations are solved with Newton–Raphson iteration method and the results are found as in Feguson's study [41]. The initial temperature before combustion reaction is calculated from the thermal equilibrium of fuel–air and steam blend as given in the following equation:

$$
T_0 = \frac{m_{af} C_{v,af} T_{af} + m_{ste} C_{v,ste} T_{ste}}{m_{af} C_{v,af} + m_{ste} C_{v,ste}} \tag{16}
$$

where $C_{v,af}$ and $C_{v,ste}$ are the specific heats at the constant volume, m_{af} and m_{ste} are the masses, T_{af} and T_{ste} are the temperatures of the air–fuel mixture and the injected steam.

3. Results and discussion

In this section, adiabatic combustion simulation with steam has been conducted for the bio fuels (COME, SFO, CSO, SBO, CO, RSO, ETH, METH) in order to examine the influences of steam injection on the equilibrium combustion products, specific heats and adiabatic combustion temperatures. The results obtained have been

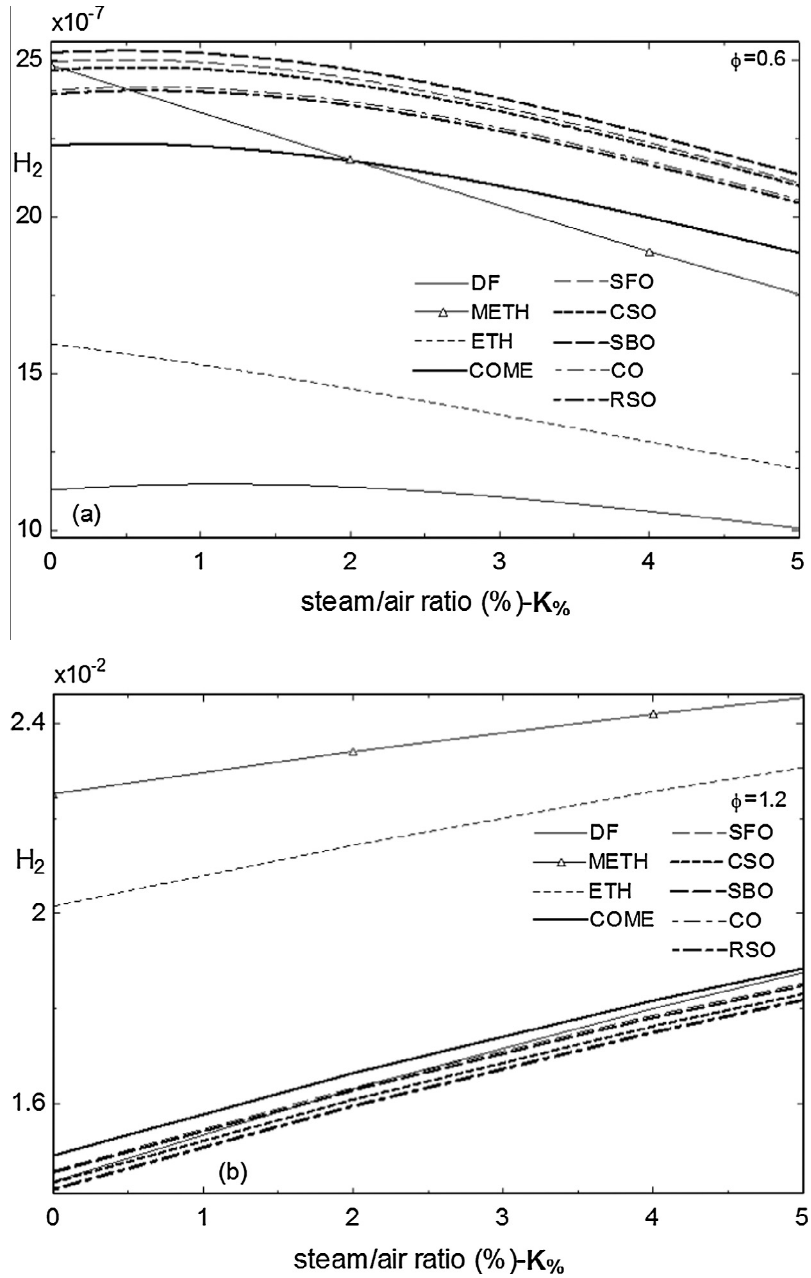


Fig. 6. Equilibrium mole fractions of H_2 with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

comparatively presented for lean and rich equivalence ratios and increasing steam injection ratios from 0% to 5%. In order to obtain numerical solutions and figures, the combustion pressure is taken as 30 atm, the steam temperature is 573 K, temperature of the air and fuel blend is accepted as 300 K before combustion reaction. The properties of the petroleum based diesel and bio fuels are given in Table 1.

Figs. 1–10 demonstrate the influence of the steam injection on the mole fractions of 10 combustion products at equilibrium for commonly used bio fuels for lean and rich combustion circumstances.

Fig. 1 demonstrates the CO_2 formation with respect to steam injection ratios for lean and rich combustion conditions. It is clear that CO_2 increases, as carbon and hydrogen rise in the fuels. While alcohols (ETH and METH) give the lowest results, oils (SFO, CSO, SBO, CO and RSO) give the highest results. Oils, conventional diesel fuel (DF) and methyl ester (COME) give close results in terms of the increment of the CO_2. It is obvious from the figure that equilibrium mole fractions of the CO_2 remarkably reduce with increasing steam ratios. Although the similar trend is seen, more CO_2 formation occurs at the rich combustion conditions.

The change of the H_2O with respect to steam injection ratios is illustrated in Fig. 2. Whilst the maximum mole fraction of H_2O is acquired with METH, the minimum mole fraction of H_2O is attained with DF. Biodiesels (oils and methyl ester) give close values to those of DF, however their values are slightly higher. As expected, the equilibrium mole fraction of H_2O increases with increasing steam injection ratios.

Fig. 3 shows the N_2 with respect to steam injection ratios. DF has the maximum values, as METH has the lowest values. Further

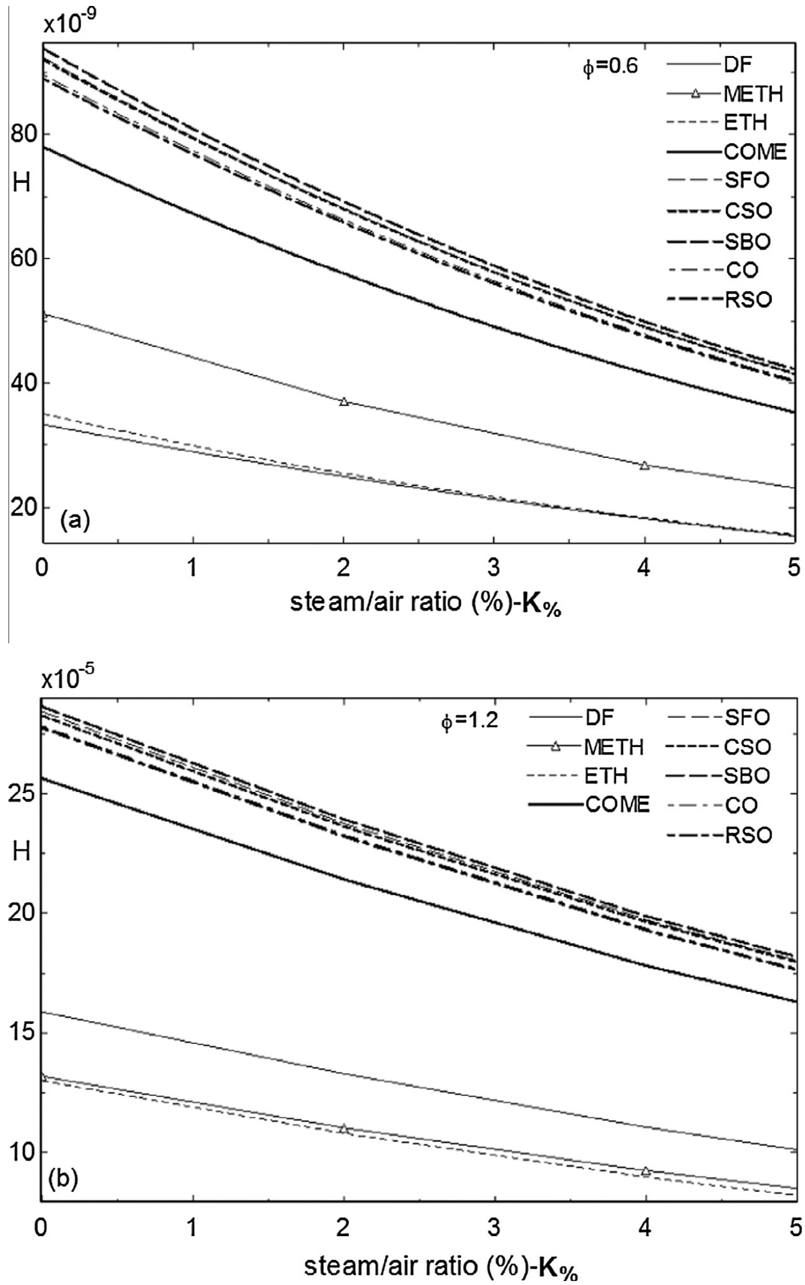


Fig. 7. Equilibrium mole fractions of H with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

N_2 is released from the combustion of DF when compared to the combustion of biodiesels. It may be seen from the figure that N_2 considerably decreases, while steam injection ratios increase.

Fig. 4 illustrates the O_2 with respect to steam injection ratios for the petroleum based diesel and bio fuels. As can be understood from the figure, the highest O_2 is formed with DF and the lowest O_2 is formed with METH in the lean combustion conditions. The O_2 formation is much lower in rich combustion conditions due to lower oxygen concentration compared to lean combustion conditions and the maximum O_2 formation happens with biodiesels, whilst the minimum O_2 formation occurs with ETH. It is clear that O_2 formation distinctively decreases, as steam ratios raise.

The change of the CO with respect to steam injection ratios is shown in Fig. 5. As expected, more CO is released in the rich combustion conditions compared to the lean combustion conditions because of higher carbon concentrations. The maximum CO formation occurs with biodiesels in the lean combustion conditions, whilst it occurs with DF in the rich combustion conditions. Even though the minimum CO is formed with ETH in the lean combustion conditions, it is formed with METH in the rich combustion conditions. It may be seen from the figure that lower CO is formed with raising steam injection ratios.

Fig. 6 shows the mole fraction of H_2 with respect to steam injection ratios. H_2 increases in the rich combustion conditions owing to higher hydrogen concentrations. The combustion of biodiesels and METH gives higher H_2 than that of ETH and DF in the lean combustion conditions. However, higher H_2 formation is acquired with the alcohols compared to the biodiesels and DF in the rich combustion

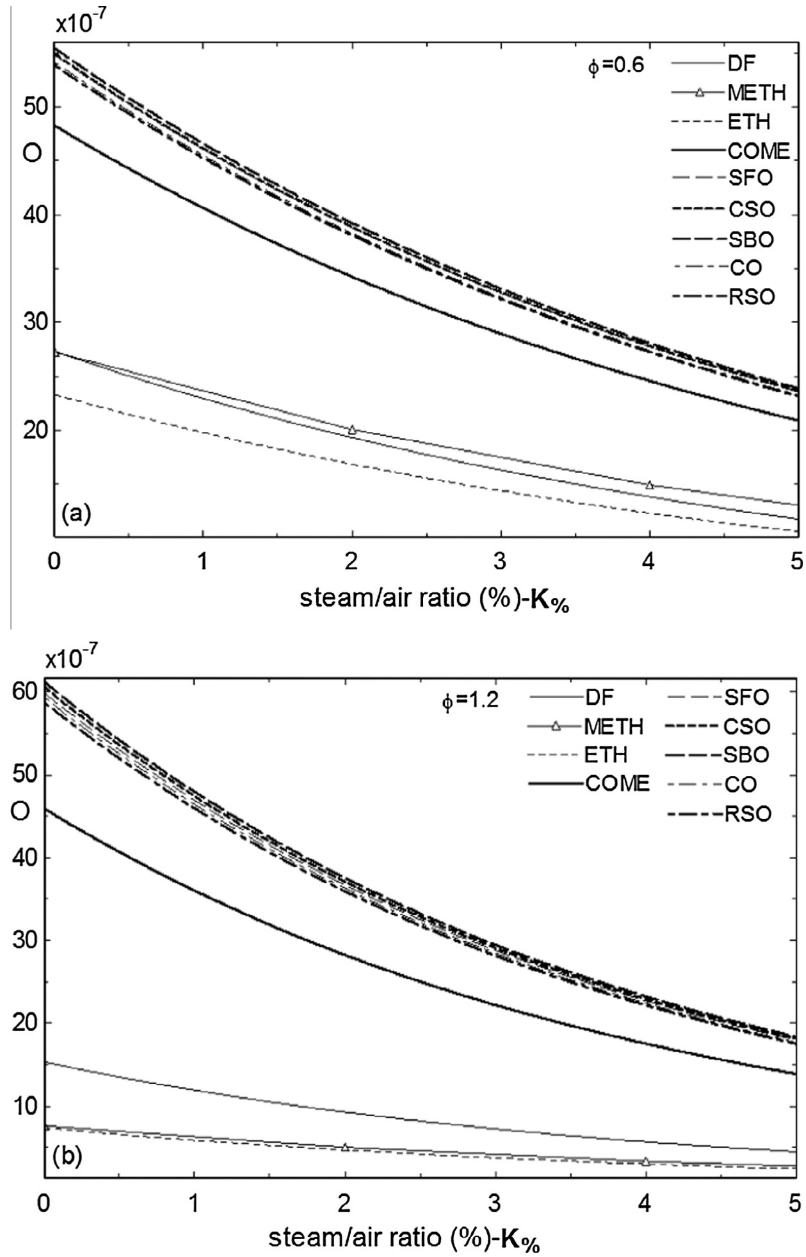


Fig. 8. Equilibrium mole fractions of O with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

conditions. Differently from previous combustion products, the formation of the H_2 reduces with increasing steam injection ratios in the lean combustion conditions, as the formation of the H_2 increases with increasing steam injection ratios in the rich combustion conditions.

Fig. 7 demonstrates the mole fraction of H with respect to steam injection ratios. H raises in the rich combustion conditions due to higher hydrogen concentrations. The combustion of biodiesels produces more H than that of the alcohols and DF in both of the lean and rich combustion conditions. Similar trend as in the Fig. 5 is seen in terms of the influence of the steam injection.

Fig. 8 shows the mole fraction of O with respect to steam injection ratios. There are no considerable differences between the lean and rich combustion conditions in terms of O formation. The combustion of biodiesels produces further O compared to the combustion of the alcohols and DF in both of the lean and rich combustion conditions. As can be observed from the figure, the increment of steam ratio decreases the O formation.

The change of the OH with respect to steam injection ratios is demonstrated in Fig. 9. A slight increase in the OH formation is observed in the rich combustion conditions compared to lean combustion conditions. As the combustion of the biodiesels releases the highest OH, other fuels release lower OH. The minimum OH formations are seen with DF and ETH in the lean and rich combustion conditions, respectively. It may be obviously seen from the figure that the application of the steam injection distinctively decreases the OH formation.

Fig. 10 illustrates the mole fraction of NO with respect to steam injection ratios. The NO formation diminishes in the rich combustion conditions due to lower oxygen concentrations. The combustion of biodiesels leads to further NO formation compared to the alcohols and DF in both of the lean and rich combustion conditions.

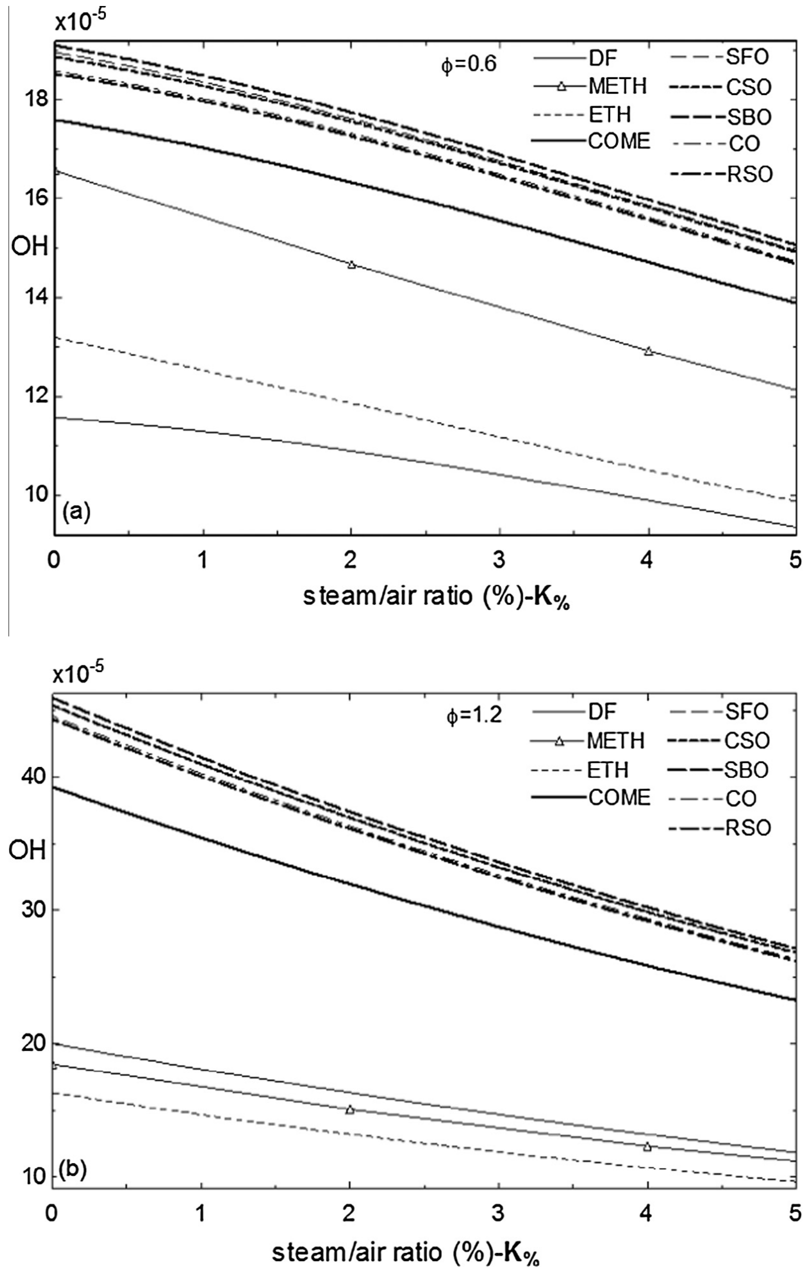


Fig. 9. Equilibrium mole fractions of OH with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

The decrease rate of NO with respect to steam injection ratio is higher for biodiesels compared to that of the other fuels in the rich combustion conditions. In the lean combustion conditions, the reduction rate is similar to each other for all fuels given in the study. It may be seen from the figure that the minimum NO formation is obtained with the combustion of ETH. As expected, the NO formation minimizes with increasing steam injection ratios.

Fig. 11 demonstrates the average specific heats at constant pressure with respect to steam injection ratios. Greater specific heats are obtained in the rich combustion conditions compared to lean combustion conditions. The highest specific heats are acquired with METH and the lowest specific heats are attained with DF. Although the biodiesels have higher specific heats than that of DF, their values are lower than those of alcohols. In both combustion conditions, specific heats increase, while steam injection ratios rise. Because the specific heat of the steam is much more than those of the combustion products at the same temperature. However, the increase rate of specific heats with respect to steam injection ratio is lower for biodiesels compared to that of the other fuels in the rich combustion conditions.

Fig. 12 illustrates the adiabatic flame temperatures of the fuels with respect to steam injection ratios. It is clearly observed that adiabatic flame temperatures of the fuels in the rich combustion conditions are higher than those in the lean combustion conditions. The biodiesels have the maximum adiabatic flame temperatures in both combustion conditions. However, the minimum adiabatic flame temperatures in the lean and rich combustion conditions are seen with ETH and METH, respectively. As may be seen from the figure, steam reduces the adiabatic flame temperatures,

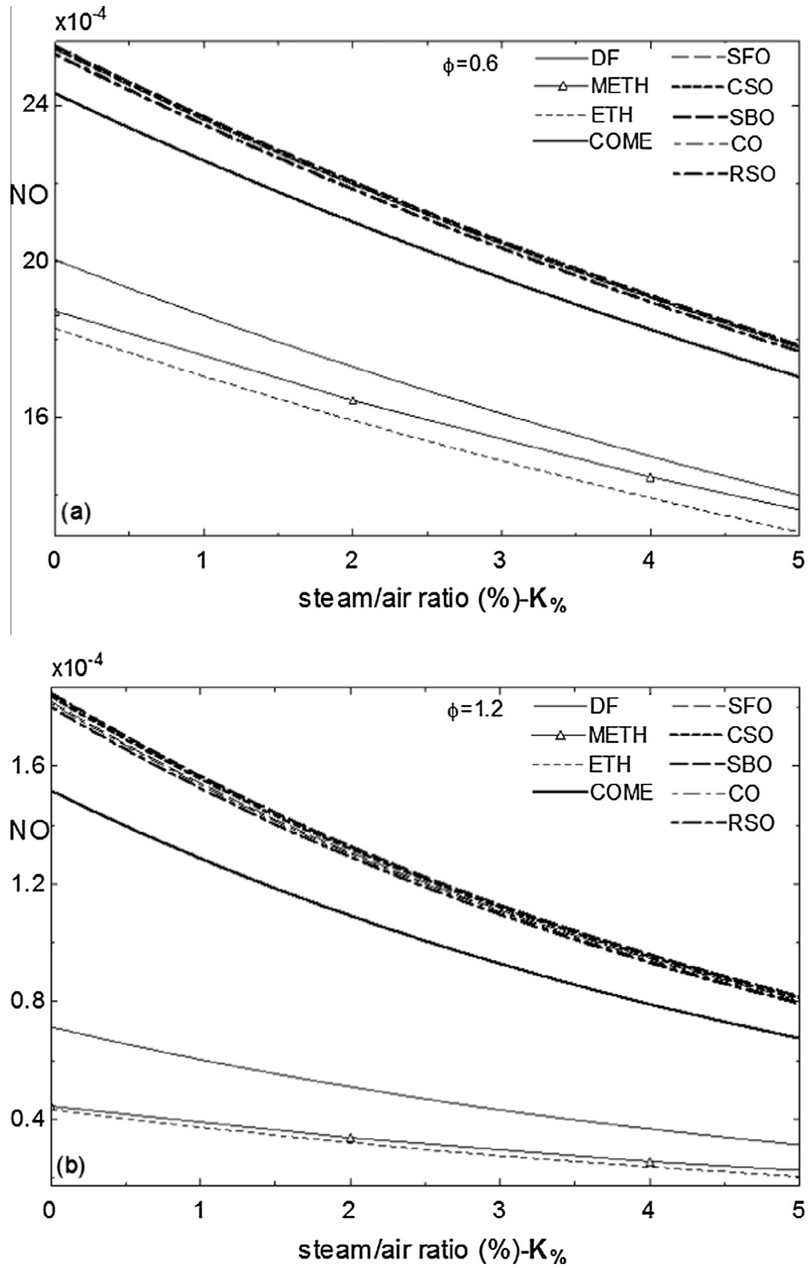


Fig. 10. Equilibrium mole fractions of NO with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

as the heat capacity of the steam is greater than that of the other combustion products.

The general effect of steam injection on the combustion of bio fuels is that the formation of the combustion products such as CO_2, N_2, O_2, CO, H, O, OH and NO is decreased and the specific heats increase as steam injection ratio increases. Therefore, this method can reduce the exhaust emissions, especially NO emissions, while the engine performance increases [33–39]. Another marked result of this study is that less CO, CO_2 and NO are formed by combustion of the alcohols [ETH and METH] compared to DF and biodiesels at the same equivalence ratios. Also, as it is mentioned above the specific heats of the alcohols are higher than those of the other fuels. Thus, the alcohols can be utilized to decrease NO emissions and increase the performance of diesel engines [39]. However, the diesel engines fuelled with biodiesel blends produce more NO emissions [12,17,28,30] and so steam injection method could be proposed as a good solution.

4. Conclusion

In this study, the influences of steam injection on the adiabatic flame temperatures, specific heats and combustion products of bio fuels have been modeled by a simulation code verified with experimental studies and two computer programs. The obtained results have been compared with the equilibrium combustion products and thermodynamic properties of the conventional diesel fuel. In the results, the maximum CO_2 formation occurs with the combustion of biodiesels, the lowest CO_2 is formed with the combustion of alcohols. The highest CO formation happens with the combustion

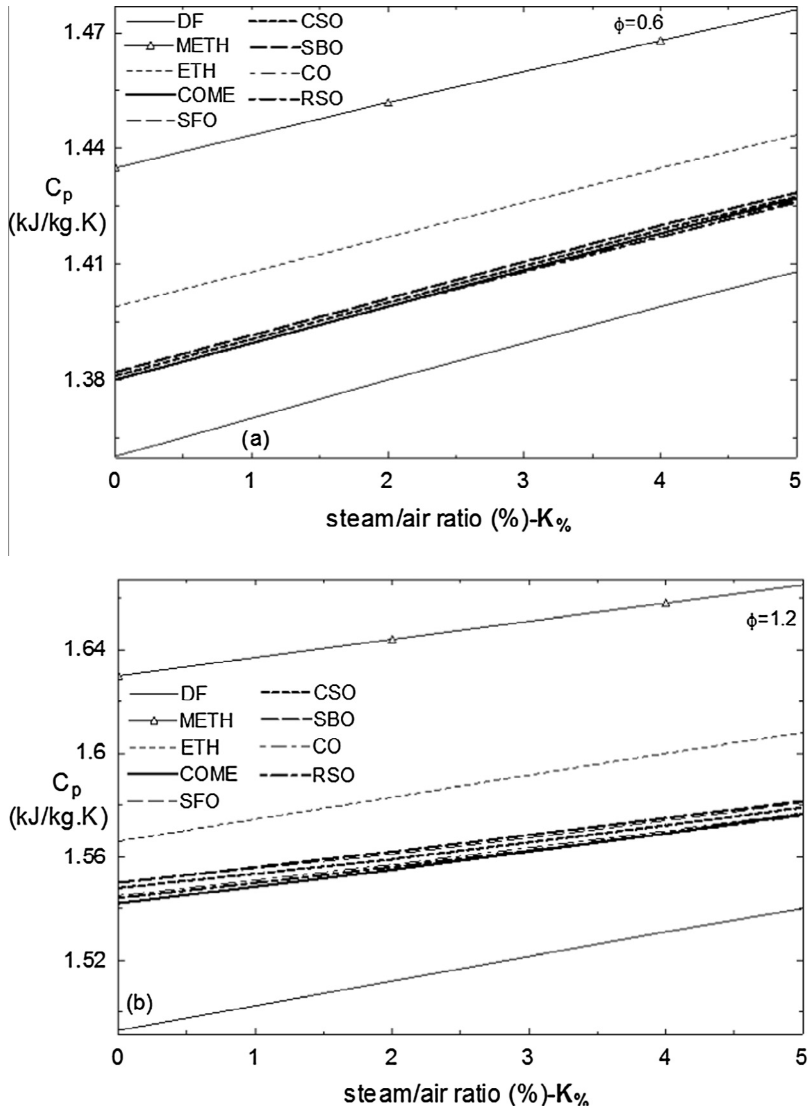


Fig. 11. Specific heats at constant pressure with respect to steam injection ratios for $\phi = 0.6$ and $\phi = 1.2$.

of biodiesels in the lean combustion conditions; on the other hand, the highest CO is formed with DF combustion in the rich conditions. The lowest CO is formed with the combustion of ETH in the lean combustion conditions and with the combustion of METH in the rich combustion conditions. The combustion of biodiesels causes further NO formation compared to the alcohols and DF. The minimum NO formation is attained with the combustion of ETH. Hence, the alcohols could be more preferable compared to biodiesel fuels in order to decrease NO emissions in diesel engines. The reduction rate of NO is higher for biodiesels compared to that of the other fuels in the rich combustion conditions. Therefore, higher steam injection ratios can be used for biodiesels in order to provide lower NO formation in the rich combustion conditions. The specific heats are greater in the rich combustion conditions than those in lean combustion conditions. The maximum specific heats are obtained with the METH and the minimum specific heats are attained with DF. Even though the combustion products of the biodiesels have higher specific heats compared to those of DF, their values are lower than those of alcohols. The increment rate of the specific heats of the biodiesels is lower than that of alcohols and DF in the rich combustion conditions. The change trend of the combustion products and thermodynamic properties of bio fuels with respect to change of steam injection ratios is generally similar to each other. The adiabatic flame temperatures of the fuels in the rich combustion conditions are higher than those in the lean combustion conditions and the biodiesels have the highest adiabatic flame temperatures. The equilibrium mole fractions of the CO_2, N_2, O_2, CO, H, O, OH and NO remarkably reduce, specific heats increase and adiabatic combustion temperatures diminishes with increasing steam ratios.

In the results, it was shown that the alcohols produce minimum NO emissions, as the biodiesels produce maximum NO emissions. If we consider that these type fuels are used in the diesel engines, this study especially is important for the researches about diesel engines. Because of higher combustion temperatures, diesel engines produce more NO emissions. Implementation of steam injection method results in less NO formation. Therefore, this method is environmentally friendly and could be used to increase the usability of bio fuels as a diesel engine fuel. The results obtained are valuable in terms of understanding the effects of steam injection and using different fuels in diesel engines on the equilibrium combustion products, specific heats and adiabatic combustion temperatures. The presented results could be used in the future studies about the bio fuels and steam injection method.

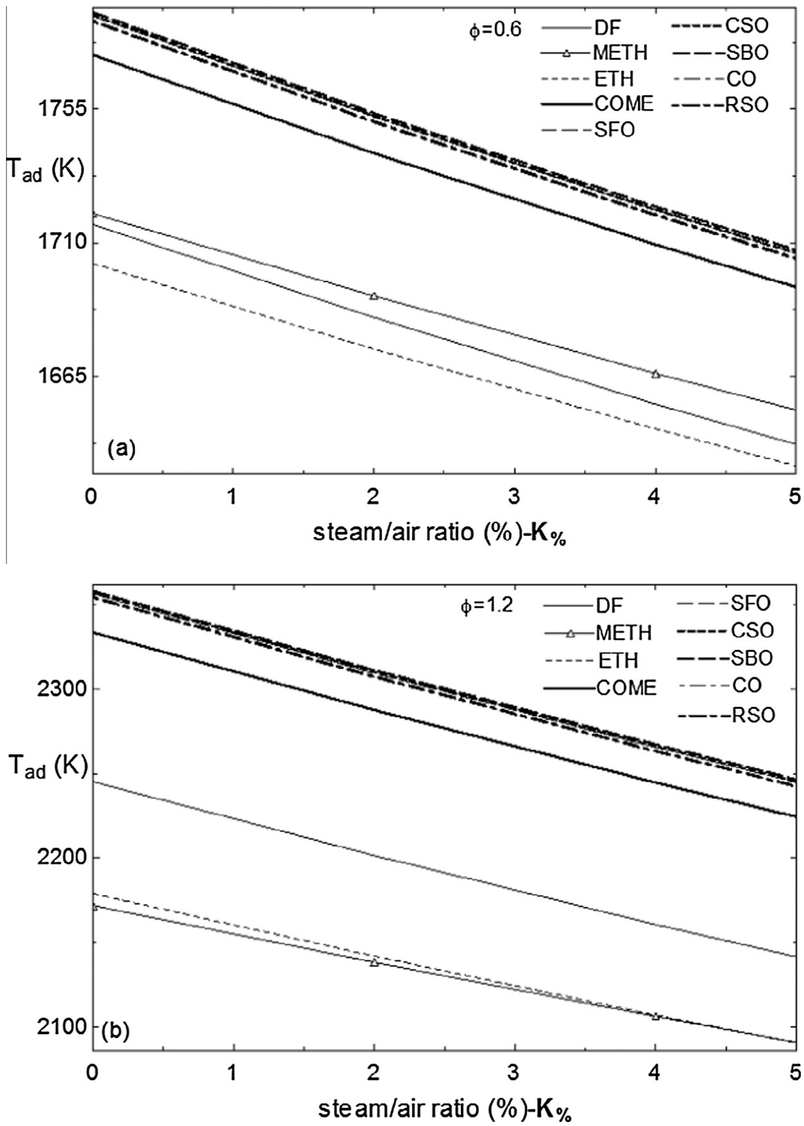


Fig. 12. Adiabatic flame temperatures with respect to steam injection ratios for ϕ = 0.6 and ϕ = 1.2.

References

[1] Banerjee R, Bose PK. An experimental investigation on the potential of hydrogen in the reduction of the emission characteristics of an existing four-stroke single-cylinder diesel engine operating under EGR. Int J Green Energy 2012;9:84–110.
[2] Altin R, Cetinkaya S, Yucesu HS. The potential of using vegetable oil fuels as fuel for diesel engines. Energy Convers Manage 2001;42: 529–38.
[3] Canakci M, Erdil A, Arcaklioglu E. Performance and exhaust emissions of a biodiesel engine. Appl Energy 2006;83:594–605.
[4] Canakci M, Ozsezen AN, Arcaklioglu E. Prediction of performance and exhaust emissions of a diesel engine fuelled with biodiesel produced from waste frying palm oil. Expert Syst Appl 2009;36:9268–80.
[5] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combust 2007;33:233–71.
[6] Sharma YC, Singh B, Upadhyay SN. Advancements in development and characterization of biodiesel: a review. Fuel 2008;87:2355–73.
[7] Patil PD, Deng S. Optimization of biodiesel production from edible and non-edible vegetable oils. Fuel 2009;88:1302–6.
[8] Fassinou WF, Steene LV, Toure S. What correlation is appropriate to evaluate biodiesels and vegetable oils higher heating value (HHV)? Fuel 2011;90:3398–403.
[9] Balat M. Potential alternatives to edible oils for biodiesel production – a review of current work. Energy Convers Manage 2011;52:1479–92.
[10] Gumus M, Sayin C, Canakci M. The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fuelled with biodiesel–diesel fuel blends. Fuel 2012;95:486–94.
[11] Sanli H, Canakci M, Alptekin E. Predicting the higher heating values of waste frying oils as potential biodiesel feedstock. Fuel 2014;115:850–4.
[12] Kannan D, Pachamuthu S, Nabi MN. Theoretical and experimental investigation of diesel engine performance, combustion and emissions analysis fuelled with the blends of ethanol, diesel and jatropha methyl ester. Energy Convers Manage 2012;63:322–31.
[13] Karabektas M, Ergen G, Hosoz M. Effects of the blends containing low ratios of alternative fuels on the performance and emission characteristics of a diesel engine. Fuel 2013;112:537–41.
[14] Hulwan DB, Joshi SV. Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content. Appl Energy 2011;88:5042–55.
[15] Saxena S, Schneider S, Aceves S. Wet ethanol in HCCI engines with exhaust heat recovery to improve the energy balance of ethanol fuels. Appl Energy 2012;98:448–57.
[16] Lei J, Shen L, Bi Y. A novel emulsifier for ethanol–diesel blends and its effect on performance and emissions of diesel engine. Fuel 2012;93:305–11.
[17] Cheng CH, Cheung CS, Chan TL. Comparison of emissions of a direct injection diesel engine operating on biodiesel with emulsified and fumigated methanol. Fuel 2008;87:1870–9.
[18] Sayin C, Ilhan M, Canakci M, Gumus M. Effect of injection timing on the exhaust emissions of a diesel engine using diesel–methanol blends. Renew Energy 2009;34:1261–9.
[19] Sayin C, Ozsezen AN, Canakci M. The influence of operating parameters on the performance and emissions of a DI diesel engine using methanol-blended-diesel fuel. Fuel 2010;89:1407–14.
[20] Zhang ZH, Cheung CS, Yao CD. Influence of fumigation methanol on the combustion and particulate emissions of a diesel engine. Fuel 2013;111:442–8.

[21] Lin H, Haagenson DM, Wiesenborn DP. Effect of trace contaminants on cold soak filterability of canola biodiesel. Fuel 2011;90:1771–7.
[22] Lee S, Posarac D, Ellis N. An experimental investigation of biodiesel synthesis from waste canola oil using supercritical methanol. Fuel 2012;91:229–37.
[23] Sayin C, Gumus M, Canakci M. Effect of fuel injection timing on the emissions of a direct-injection diesel engine fuelled with canola oil methyl ester–diesel fuel blends. Energy Fuels 2010;24:2675–82.
[24] Saka S, Kusdiana D. Biodiesel fuel from rapeseed oil as prepared in supercritical methanol. Fuel 2001;80:225–31.
[25] Wang B, Li S, Tian S. A new solid base catalyst for the transesterification of rapeseed oil to biodiesel with methanol. Fuel 2013;104:698–703.
[26] Candeia RA, Silva MCD, Filho JRC. Influence of soybean biodiesel content on basic properties of biodiesel–diesel blends. Fuel 2009;88:738–43.
[27] Bazooyar B, Ghorbani A, Shariati A. Combustion performance and emissions of petrodiesel and biodiesels based on various vegetable oils in a semi industrial boiler. Fuel 2011;90:3078–92.
[28] Randazzo ML, Sodré JR. Exhaust emissions from a diesel powered vehicle fuelled by soybean biodiesel blends (B3–B20) with ethanol as an additive (B20E2–B20E5). Fuel 2011;90:98–103.
[29] Santos EM, Piovesan ND, Barros EG. Low linolenic soybeans for biodiesel: characteristics, performance and advantages. Fuel 2013;104:861–4.
[30] Ozener O, Yuksek L, Ergenc AT. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 2014;115:875–83.
[31] Selim MYE. Effect of exhaust gas recirculation on some combustion characteristics of dual fuel engine. Energy Convers Manage 2003;44:707–21.
[32] Abd-Alla GH, Soliman HA, Badr OA, Abd-Rabbo MF. Effects of diluent admissions and intake air temperature in exhaust gas recirculation on the emissions of an indirect injection dual fuel engine. Energy Convers Manage 2001;42:1033–45.
[33] Parlak A, Ayhan V, Üst Y, Sahin B, Cesur I, Boru B, et al. New method to reduce NOx emissions of diesel engines: electronically controlled steam injection system. J Energy Inst 2012;85:135–9.
[34] Gonca G. Investigation of the effect of steam injection on performance and emissions in a turbocharged diesel engine running with the miller cycle. PhD thesis. Yildiz Technical University; 2013.
[35] Gonca G, Sahin B, Ust Y, Parlak A, Safa A. Comparison of steam injected diesel engine and miller cycled diesel engine by using two zone combustion model. J Energy Inst 2014. http://dx.doi.org/10.1016/j.joei.2014.04.007 [in press].
[36] Gonca G, Sahin B, Ust Y, Parlak A. Determination of the optimum temperatures and mass ratios of steam injected into turbocharged internal combustion engines. J Renew Sustain Energy 2013;023119(5):1–13. http://dx.doi.org/10.1063/1.4798313.
[37] Kokkulunk G, Gonca G, Ayhan V, Cesur I, Parlak A. Theoretical and experimental investigation of diesel engine with steam injection system on performance and emission parameters. Appl Therm Eng 2013;54:161–70.
[38] Cesur I, Parlak A, Ayhan A, Boru B, Gonca G. The effects of electronic controlled steam injection on spark ignition engine. Appl Therm Eng 2013;55:61–8.
[39] Gonca G. Investigation of the effects of steam injection on performance and NO emissions of a diesel engine running with ethanol–diesel blend. Energy Convers Manage 2014;77:450–7.
[40] Kayadelen HK, Ust Y. Prediction of equilibrium products and thermodynamic properties in H_2O injected combustion for CHON type fuels. Fuel 2013;113:389–401.
[41] Ferguson CR. Internal combustion engines – applied thermosciences. New York: John Wiley & Sons Inc.; 1986.
[42] Sayin C. Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. Fuel 2010;89:3410–5.
[43] Kokkulunk G, Gonca G, Parlak A. The effects of design parameters on performance and no emissions of steam-injected diesel engine with exhaust gas recirculation. Arab J Sci Eng 2014;39(5):4119–29.
[44] Kokkulunk G, Parlak A, Ayhan V, Cesur I, Gonca G, Boru B. Theoretical and experimental investigation of steam injected diesel engine with EGR. Energy 2014;74:331–9.
[45] Gonca G, Sahin B, Parlak A, Ust Y, Ayhan V, Cesur I, et al. The effects of steam injection on the performance and emission parameters of a miller cycle diesel engine. Energy 2014;78:266–75.
[46] Gonca G, Sahin B, Parlak A, Ust Y, Ayhan V, Cesur I, et al. Theoretical and experimental investigation of the Miller cycle diesel engine in terms of performance and emission parameters. Appl Energy 2015;138:11–20.